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# (54) MILLIMETER-WAVE COMMUNICATION STATION AND METHOD FOR MULTIPLE-ACCESS BEAMFORMING IN A MILLIMETER-WAVE COMMUNICATION NETWORK

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***H04W 72/04*** (2009.01)
***H04B 7/06*** (2006.01)

(52) **U.S. Cl.**
CPC ......... ***H04W 72/0446*** (2013.01); ***H04B 7/0617*** (2013.01); ***H04B 7/0619*** (2013.01)

(58) **Field of Classification Search**
USPC .......................................................... 370/339
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,386,305 B2 6/2008 Etkin et al.
8,331,265 B2 * 12/2012 Yong et al. .................... 370/254

(Continued)

FOREIGN PATENT DOCUMENTS

CN 104079334 A 10/2014
JP 2012501591 A 1/2012

(Continued)

OTHER PUBLICATIONS

"U.S. Appl. No. 12/574,140, Final Office Action mailed Mar. 12, 2013", 41 pgs.

(Continued)

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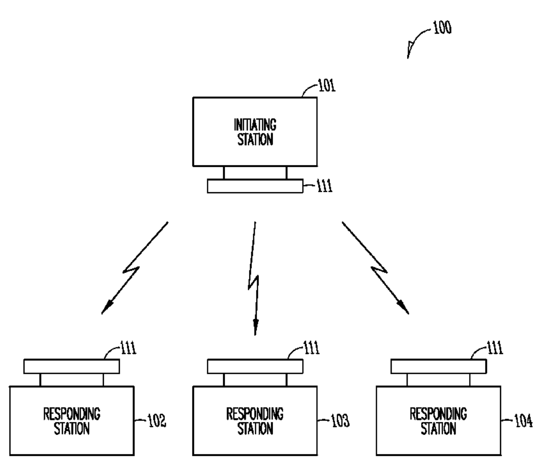
(74) *Attorney, Agent, or Firm* — Schwegman Lundberg & Woessner, P.A.

(57) **ABSTRACT**

Embodiments of a millimeter-wave communication station and method for multiple-access beamforming in a millimeter-wave network are generally described herein. In some embodiments, an initiating station performs multiple-access beamforming with one or more responding stations by announcing a number of sector-sweep (SS) slots of a beamforming training (BFT) period and a number of SS frames of each SS slot. One or more SS frames are received from one or more of the responding stations within one of the SS slots of the BFT period. The initiating station transmits one or more SS feedback frames to the responding stations within the one SS slot to indicate an antenna configuration to the responding stations for communication with the initiating station. The responding stations transmit a limited number of SS frames per SS slot based on the number of SS frames announced by the initiating station and transmit any additional SS frames in a next SS slot of the beamforming training period. Each SS frame contains an indication to the initiating station of an antenna configuration for communication with the responding station.

**24 Claims, 6 Drawing Sheets**




MILLIMETER-WAVE COMMUNICATION NETWORK

(56) **References Cited**

U.S. PATENT DOCUMENTS

| | | | | |
|---|---|---|---|---|
| 8,335,167 | B1 * | 12/2012 | Zhang et al. | 370/252 |
| 8,422,961 | B2 * | 4/2013 | Kafle | 455/67.14 |
| 8,625,565 | B2 | 1/2014 | Cordeiro et al. | |
| 2002/0061730 | A1 * | 5/2002 | Hart et al. | 370/336 |
| 2003/0195017 | A1 | 10/2003 | Chen et al. | |
| 2004/0038658 | A1 | 2/2004 | Gurelli et al. | |
| 2004/0203905 | A1 | 10/2004 | Cuffaro | |
| 2004/0204106 | A1 | 10/2004 | Gurelli et al. | |
| 2005/0147115 | A1 | 7/2005 | Li et al. | |
| 2005/0277444 | A1 | 12/2005 | Rensburg et al. | |
| 2006/0052114 | A1 | 3/2006 | Cuffaro | |
| 2006/0105771 | A1 | 5/2006 | Iacono et al. | |
| 2006/0164969 | A1 | 7/2006 | Malik et al. | |
| 2006/0172710 | A1 | 8/2006 | Cahana et al. | |
| 2006/0240780 | A1 | 10/2006 | Zhu et al. | |
| 2007/0191063 | A1 | 8/2007 | Iacono et al. | |
| 2007/0230373 | A1 | 10/2007 | Li et al. | |
| 2007/0232245 | A1 | 10/2007 | Cheng | |
| 2007/0238156 | A1 | 10/2007 | Hughes et al. | |
| 2008/0165720 | A1 | 7/2008 | Hu et al. | |
| 2008/0181344 | A1 | 7/2008 | Jiang et al. | |
| 2008/0194204 | A1 | 8/2008 | Duet et al. | |
| 2009/0061784 | A1 | 3/2009 | Cordeiro | |
| 2009/0232023 | A1 | 9/2009 | Soffer et al. | |
| 2009/0232240 | A1 | 9/2009 | Lakkis | |
| 2009/0232245 | A1 | 9/2009 | Lakkis | |
| 2009/0238156 | A1 | 9/2009 | Yong et al. | |
| 2010/0054223 | A1 * | 3/2010 | Zhang et al. | 370/338 |
| 2010/0056062 | A1 * | 3/2010 | Zhang et al. | 455/63.1 |
| 2010/0103045 | A1 * | 4/2010 | Liu et al. | 342/372 |
| 2010/0111215 | A1 | 5/2010 | Nandagopalan et al. | |
| 2010/0118716 | A1 | 5/2010 | Lakkis et al. | |
| 2010/0118835 | A1 * | 5/2010 | Lakkis et al. | 370/336 |
| 2010/0142443 | A1 | 6/2010 | Chou et al. | |
| 2010/0214169 | A1 * | 8/2010 | Kafle | 342/368 |
| 2010/0215027 | A1 * | 8/2010 | Liu et al. | 370/338 |
| 2010/0265922 | A1 * | 10/2010 | Bracha | 370/336 |
| 2010/0265924 | A1 * | 10/2010 | Yong et al. | 370/336 |
| 2010/0265925 | A1 * | 10/2010 | Liu et al. | 370/336 |
| 2011/0064033 | A1 | 3/2011 | Gong et al. | |
| 2011/0069688 | A1 * | 3/2011 | Zhang et al. | 370/338 |
| 2011/0080898 | A1 | 4/2011 | Cordeiro et al. | |
| 2011/0110340 | A1 * | 5/2011 | Lakkis | H04W 74/08 370/336 |

FOREIGN PATENT DOCUMENTS

| | | | |
|---|---|---|---|
| JP | 2012507946 | A | 3/2012 |
| JP | 2012524459 | A | 10/2012 |
| JP | 2013504974 | A | 2/2013 |
| RU | 2496231 | C1 | 10/2013 |
| WO | WO-2006049714 | A2 | 5/2006 |
| WO | WO-2011043901 | A2 | 4/2011 |
| WO | WO-2011043901 | A3 | 4/2011 |

OTHER PUBLICATIONS

"U.S. Appl. No. 12/574,140, Non Final Office Action mailed Aug. 22, 2012", 34 pgs.

"U.S. Appl. No. 12/574,140, Notice of Allowance mailed Sep. 4, 2013", 11 pgs.

"U.S. Appl. No. 12/574,140, Response filed May 22, 2013 to Final Office Aciton mailed Mar. 12, 2013", 13 pgs.

"U.S. Appl. No. 12/574,140, Response filed Nov. 21, 2012 to Non Final Office Action mailed Aug. 22, 2012", 15 pgs.

"Chinese Application Serial No. 201010506918.5, Office Action mailed Mar. 5, 2013", 13 pgs.

"Chinese Application Serial No. 201010506918.5, Office Action mailed Sep. 12, 2013", 7 pgs.

"Chinese Application Serial No. 201010506918.5, Response filed Jul. 20, 2013 to Office Action mailed Mar. 5, 2013", 12 pgs.

"European Application Serial No. 10822408.0, Response filed Jun. 22, 2012 to Office Action mailed May 15, 2012", 36 pgs.

"International Application Serial No. PCT/US2010/048724, International Preliminary Report on Patentability mailed Apr. 19, 2012", 6 pgs.

"International Application Serial No. PCT/US2010/048724, Search Report mailed May 26, 2011", 5 pgs.

"International Application Serial No. PCT/US2010/048724, Written Opinion mailed May 26, 2011", 4 pgs.

"Japanese Application Serial No. 2012-533192, Office Action mailed Jun. 4, 2013", 3 pgs.

"Japanese Application Serial No. 2012-533192, Response filed Aug. 15, 2013 to Office Action mailed Jun. 4, 2013", 12 pgs.

"European Application Serial No. 10822408.0, Extended European Search Report mailed Dec. 4, 2014", 4 pgs.

"European Application Serial No. 14163996.3, Extended European Search Report mailed Dec. 16, 2014", 7 pgs.

"European Application Serial No. 14163996.3, Office Action mailed Jan. 19, 2015", 2 pgs.

"European Application Serial No. 14163996.3, Response filed Jul. 14, 2015 to Office Action mailed Jan. 19, 2015", 12 pgs.

* cited by examiner

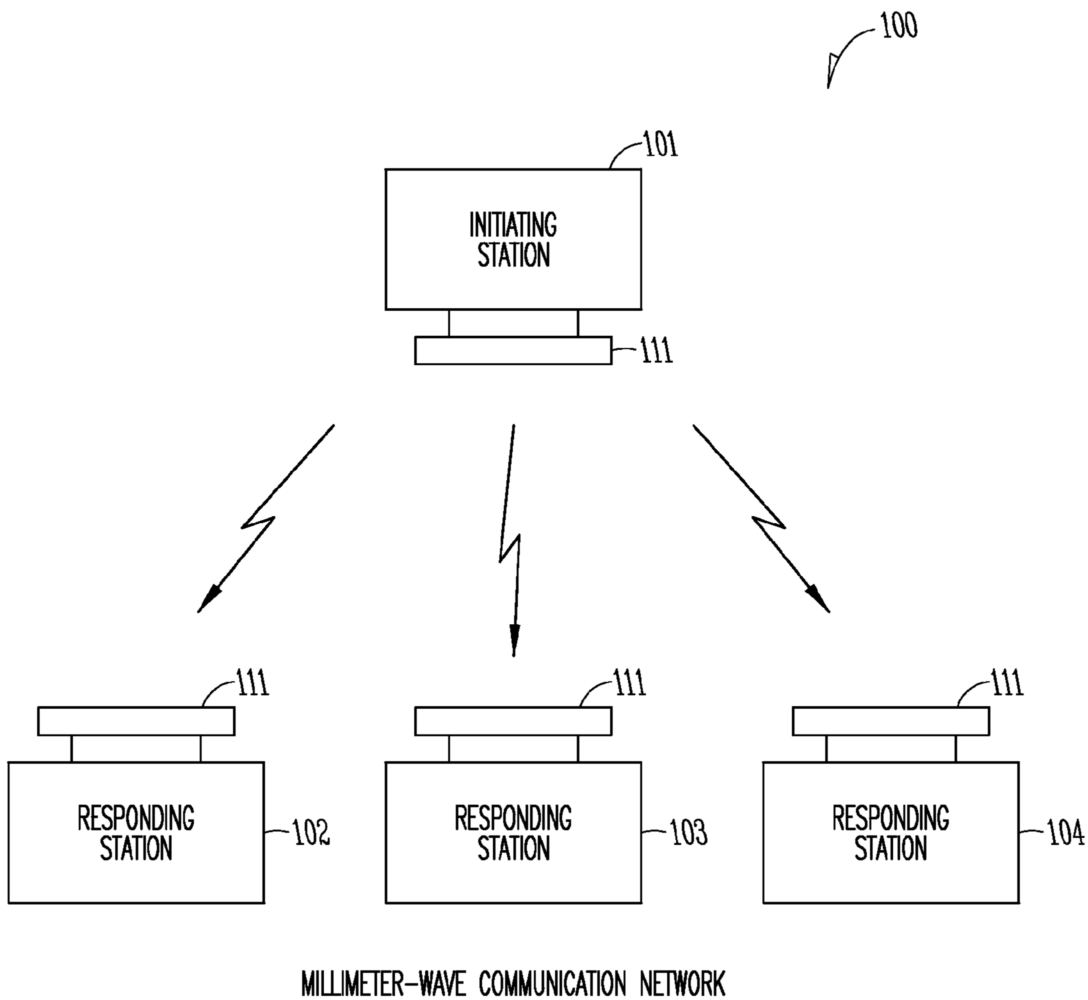
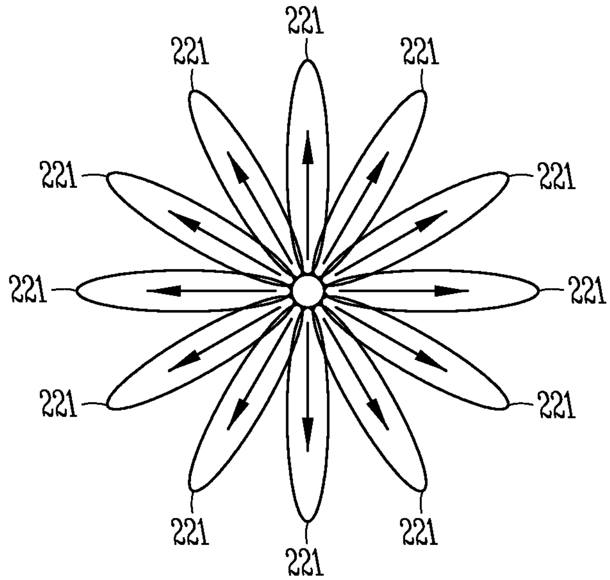
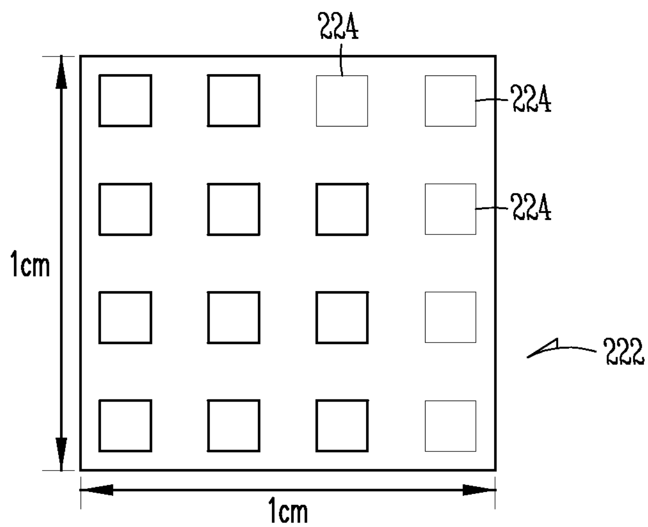

100
101
INITIATING STATION
111
111
111
111
RESPONDING STATION
102
RESPONDING STATION
103
RESPONDING STATION
104
MILLIMETER-WAVE COMMUNICATION NETWORK

*FIG. 1*




ANTENNA SECTORS

*FIG. 2A*




PORTION OF AN ANTENNA ARRAY

*FIG. 2B*

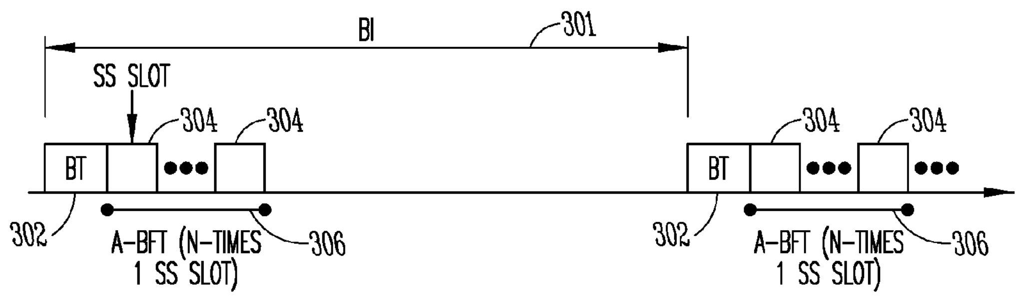

BI
301
SS SLOT
304
304
BT
302
A-BFT (N-TIMES 1 SS SLOT)
306
304
304
BT
302
A-BFT (N-TIMES 1 SS SLOT)
306

FIG. 3

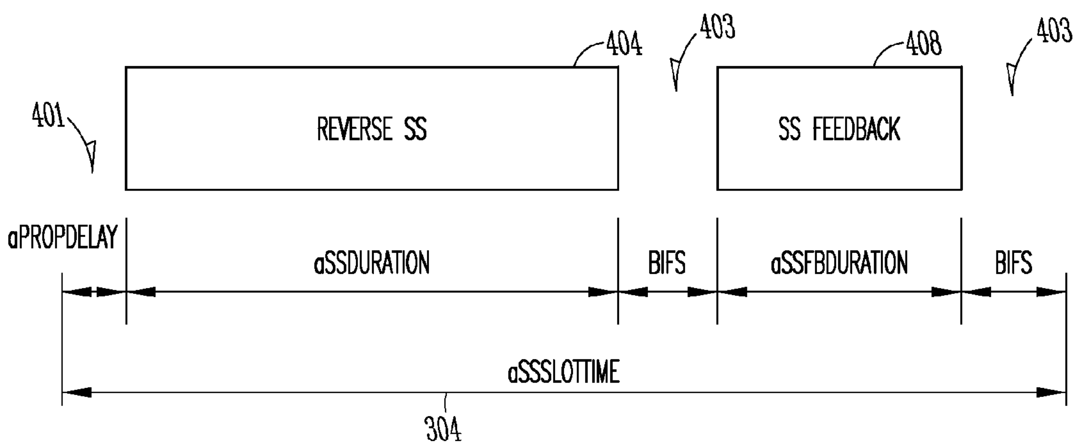

404
403
408
403
401
REVERSE SS
SS FEEDBACK
aPROPDELAY
aSSDURATION
BIFS
aSSFBDURATION
BIFS
aSSSLOTTIME
304

FIG. 4

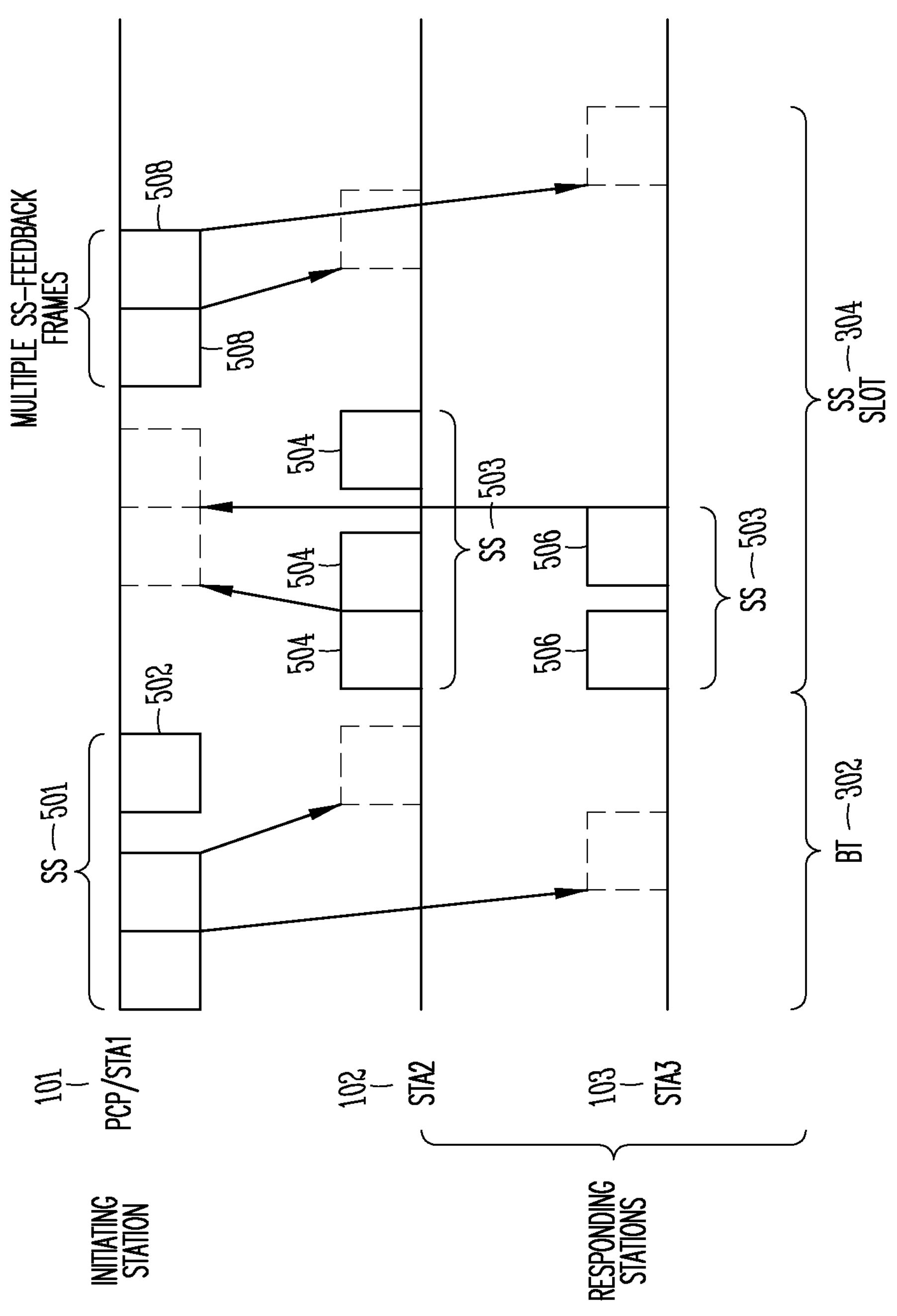

INITIATING STATION
RESPONDING STATIONS
101
PCP/STA1
102
STA2
103
STA3
SS 501
502
504
504
504
SS 503
506
506
SS 503
MULTIPLE SS-FEEDBACK FRAMES
508
508
BT 302
SS SLOT 304

FIG. 5

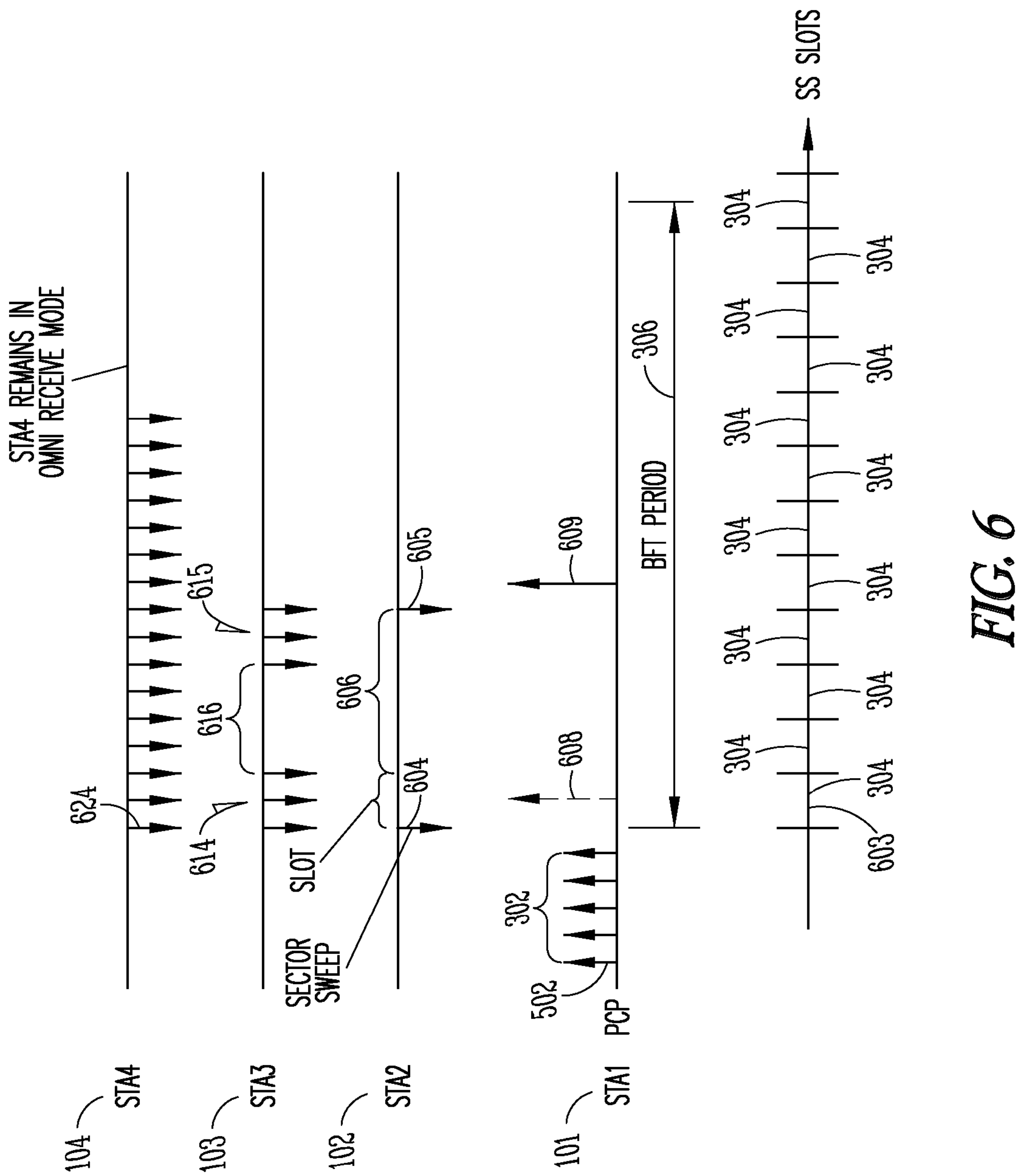

STA4 REMAINS IN OMNI RECEIVE MODE
SS SLOTS
BFT PERIOD
SECTOR SWEEP
SLOT
PCP
STA1
STA2
STA3
STA4
101
102
103
104
302
304
306
502
603
604
605
606
608
609
614
615
616
624

FIG. 6

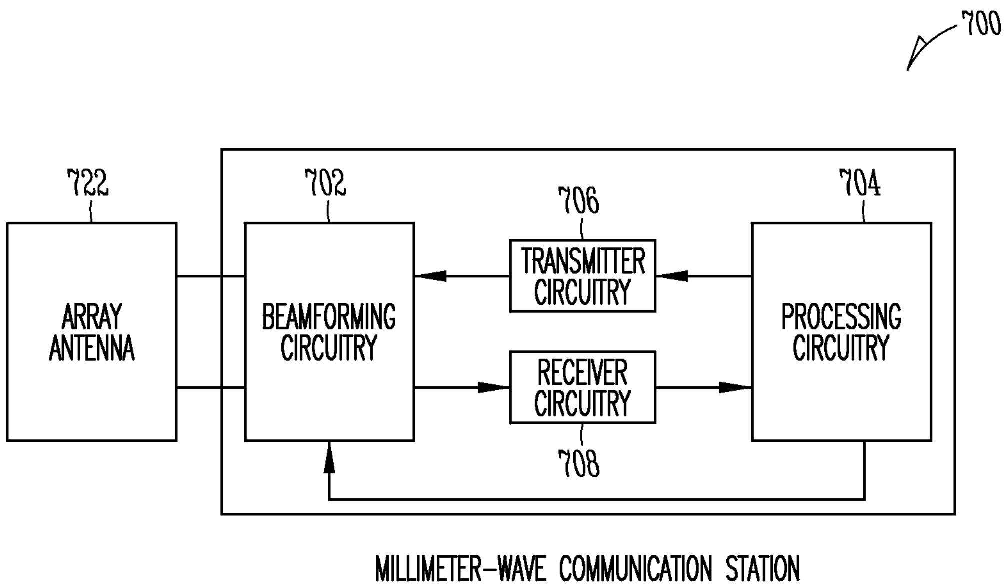

700
722
ARRAY ANTENNA
702
BEAMFORMING CIRCUITRY
706
TRANSMITTER CIRCUITRY
RECEIVER CIRCUITRY
708
704
PROCESSING CIRCUITRY
MILLIMETER-WAVE COMMUNICATION STATION

FIG. 7

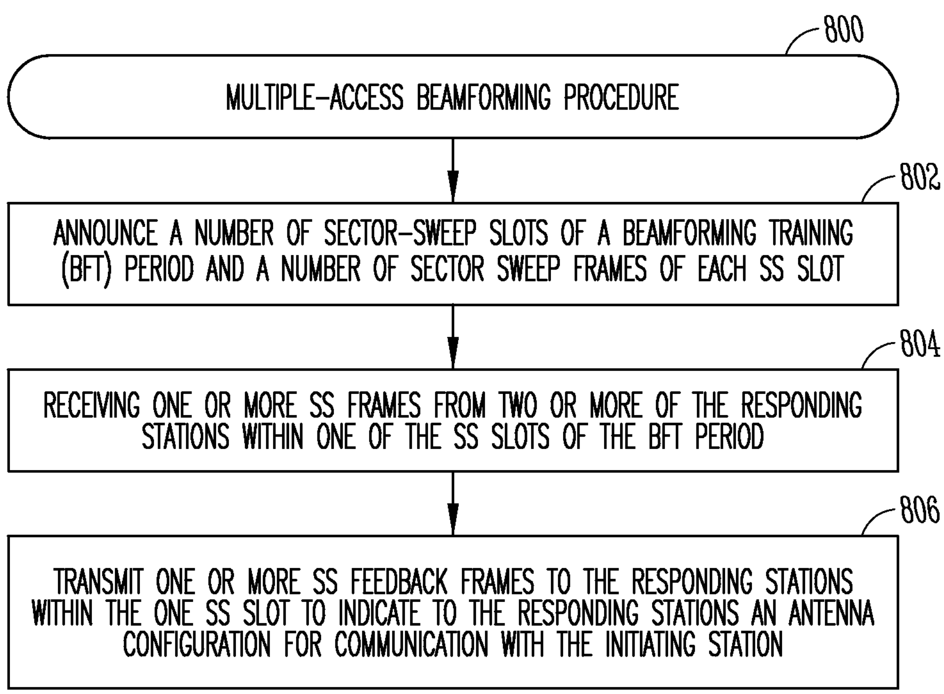

800
MULTIPLE-ACCESS BEAMFORMING PROCEDURE
802
ANNOUNCE A NUMBER OF SECTOR-SWEEP SLOTS OF A BEAMFORMING TRAINING (BFT) PERIOD AND A NUMBER OF SECTOR SWEEP FRAMES OF EACH SS SLOT
804
RECEIVING ONE OR MORE SS FRAMES FROM TWO OR MORE OF THE RESPONDING STATIONS WITHIN ONE OF THE SS SLOTS OF THE BFT PERIOD
806
TRANSMIT ONE OR MORE SS FEEDBACK FRAMES TO THE RESPONDING STATIONS WITHIN THE ONE SS SLOT TO INDICATE TO THE RESPONDING STATIONS AN ANTENNA CONFIGURATION FOR COMMUNICATION WITH THE INITIATING STATION

FIG. 8

# MILLIMETER-WAVE COMMUNICATION STATION AND METHOD FOR MULTIPLE-ACCESS BEAMFORMING IN A MILLIMETER-WAVE COMMUNICATION NETWORK

This application is a continuation of U.S. patent application Ser. No. 12/574,140, filed on Oct. 6, 2009, now issued as U.S. Pat. No. 8,625,565, which is incorporated herein by reference in its entirety.

## TECHNICAL FIELD

Embodiments pertain to millimeter-wave communication stations and methods for performing beamforming. Some embodiments pertain to wireless networks that use millimeter-wave frequencies to communicate, such as wireless personal area networks (WPANs) and wireless local area networks (WLANs). Some embodiments relate to millimeter-wave networks operating in accordance with specifications of the wireless gigabit alliance (WGA).

## BACKGROUND

Many conventional wireless networks communicate using microwave frequencies generally ranging between two and ten gigahertz (GHz). These systems generally employ either omnidirectional or low-directivity antennas primarily because of the comparatively long wavelengths of the frequencies used. The low directivity of these antennas limits the throughput of such systems, making applications such as real-time video streaming and high-definition television (HDTV) difficult to implement. The millimeter-wave band has the available spectrum and is capable of providing significantly higher-level throughputs; however, due to higher attenuation levels of millimeter-waves, more directional antennas and beamforming techniques are employed. Beamforming allows a pair of stations to achieve a desirable link budged for subsequent communications.

One issue with millimeter-wave networks is collisions that occur between communication stations attempting to establish or reestablish a link and perform beamforming training. Conventionally, only a single communication station at a time is able to perform beamforming training with the network coordinator (e.g., a Piconet Coordinator Point (PCP), Access Point, or Coordination Point). This may result in a significant delay when multiple responding stations are attempting to establish or reestablish a link at the same time (i.e. within the same beacon interval).

Thus, there are general needs for millimeter-wave communication stations and methods for multiple-access beamforming that allow more than one responding station to perform beamforming training with a network coordinator.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a millimeter-wave communication network, in accordance with some embodiments;

FIG. **2**A illustrates a plurality of antenna sectors provided by an array antenna of a millimeter-wave communication station, in accordance with some embodiments;

FIG. **2**B illustrates a portion of an array antenna, in accordance with some embodiments;

FIG. **3** illustrates the slot structure of a beamforming training period, in accordance with some embodiments;

FIG. **4** illustrates a configuration of a sector-sweep slot, in accordance with some embodiments;



FIG. **5** illustrates communications between an initiating station and responding stations for multiple-access beamforming, in accordance with some embodiments;

FIG. **6** illustrates communications between an initiating station and responding stations for multiple-access beamforming, in accordance with some alternate embodiments;

FIG. **7** is a block diagram of a millimeter-wave communication station, in accordance with some embodiments; and

FIG. **8** is a procedure for multiple-access beamforming, in accordance with some embodiments.

## DETAILED DESCRIPTION

The following description and the drawings sufficiently illustrate specific embodiments to enable those skilled in the art to practice them. Other embodiments may incorporate structural, logical, electrical, process, and other changes. Portions and features of some embodiments may be included in, or substituted for, those of other embodiments. Embodiments set forth in the claims encompass all available equivalents of those claims.

FIG. **1** is a millimeter-wave communication network in accordance with some embodiments. Millimeter-wave communication network **100** includes a plurality of millimeter-wave communication stations **101**-**104** that communicate using millimeter waves. Millimeter-wave communication stations **101**-**104** may utilize array antennas **111** to communicate within one or more antenna sectors. One of the stations, such as communication station **101**, may act as the network coordinator (such as a PCP) to coordinate communications among the communication stations **101**-**104** and control access to the wireless medium. The network coordinator may broadcast a beacon frame that indicates the length of a beacon interval during which communications are to take place. The beacon frame may be received by the other stations **102**-**104**, thereby informing the other stations **102**-**104** as to when the next beacon interval will occur. In some embodiments, the next beacon interval may be identified by a beacon transmission.

In accordance with some embodiments, communication station **101** may act as an initiating station to initiate beamforming training (BFT) with other communication stations, such as stations **102**-**104**, which may be referred to as responding stations. In these embodiments, the initiating station **101** may perform multiple-access beamforming with one or more responding stations, such as responding stations **102** and **103**. The initiating station **101** may announce a number of sector-sweep (SS) slots of a BFT period and a number of SS frames within each SS slot. The initiating station **101** may receive one or more SS frames from two or more of the responding stations within one of the SS slots of the BFT period and may transmit one or more SS feedback frames to the responding stations within the one SS slot to indicate an antenna configuration to the responding stations for communication with the initiating station **101**. The indicated antenna configuration may refer to a particular antenna sector.

The responding stations transmit a limited number of SS frames per SS slot based on the number of SS frames announced by the initiating station **101**. The responding stations may transmit any additional SS frames in a next SS slot of the beamforming training period. Accordingly, more than one responding station can perform beamforming within a beacon interval. Furthermore, the limitation on the number of SS frames within an SS slot helps reduce collisions, which may increase the success rate of SS frames being received by the initiating station **101**. For multiple-access beamforming, the initiating station is configured to receive at least two reverse sector-sweep frames from two or more of the responding stations within either a single sector-sweep slot or separate sector-sweep slots of the beamforming training period. These embodiments are described in more detail below.

In some embodiments, communication stations **101-104** may use the same frequency band for transmitting and receiving. In these embodiments, the communication stations **101-104** may employ a time-division multiplexed (TDM) communication technique.

In some embodiments, communication stations **101-104** of millimeter-wave communication network **100** may communicate substantially in accordance with specific communication standards or proposed specifications, such as the Institute of Electrical and Electronics Engineers (IEEE) standards, including the IEEE 802.15 standards and proposed specifications for millimeter-wave communications (e.g., the IEEE 802.15 task group 3c Call For Intent (CFI) dated December 2005), although the scope of the invention is not limited in this respect as they may also be suitable to transmit and/or receive communications in accordance with other techniques and standards. For more information with respect to the IEEE 802.15 standards, please refer to "IEEE Standards for Information Technology—Telecommunications and Information Exchange between Systems"—Part 15. In some embodiments, communication stations **101-104** of millimeter-wave communication network **100** may communicate substantially in accordance within accordance with specifications of the WGA.

FIG. **2**A illustrates a plurality of antenna sectors provided by an array antenna of a millimeter-wave communication station, in accordance with some embodiments. An array antenna, such as array antenna **111** (FIG. **1**), may be used to provide the plurality of antenna sectors **221**. Although FIG. **2**A shows only twelve antenna sectors **221** for illustrative purposes, array antenna **111** may provide a lesser or greater number of antenna sectors **221**. In some embodiments, the array antenna **111** may provide up to fifty or more antenna sectors **221**.

FIG. **2**B illustrates a portion of an array antenna, in accordance with some embodiments. In these embodiments, portion **222** may be a portion of an array antenna, such as array antenna **111** (FIG. **1**), and may comprise a plurality of antenna elements **224** configured to transmit and receive millimeter-wave signals within antenna sectors **221** (FIG. **2**A) utilizing beamforming techniques. The plurality of antenna elements **224** may provide a higher gain and allow beamwidth and beam direction to be controlled by signal processing techniques either in analog or digital domain. In these embodiments, array antenna **111** may operate as a phased array with a predetermined spacing between the antenna elements **224**.

In some embodiments, the millimeter-wave communication stations **101-104** (FIG. **1**) may utilize one or more array antennas **111** which may be configured to selectively transmit in each antenna sector **221**. In some embodiments, at least two antenna elements **224** may be used per each antenna sector **221**. In some embodiments, the array antenna **111** may comprise up to **64** or more antenna elements **224** configurable to transmit in any one or more of the antenna sectors **221**.

FIG. **3** illustrates the slot structure of a beamforming training period, in accordance with some embodiments. Beacon interval (BI) **301** includes a BFT period **306**, which may comprise a number of SS slots **304** and may be preceded by one or more beacon transmissions, which may be collectively referred to as beacon time (BT) **302**. Beacon intervals **301** may repeat on a regular basis as illustrated.

In accordance with multiple-access beamforming embodiments, the initiating station may announce the number of SS slots **304** of the BFT period **306** and the number of sector sweep SS frames of each SS slot **304** in a beacon transmission of the current beacon interval **301**. A beacon transmission may comprise a sector sweep comprising beacon frames transmitted by the initiating station **101** for receipt by responding stations, such as responding stations **102-104**. In these embodiments, the announced number of SS slots **304** of the BFT period **306** may follow the BT **302** in the current beacon interval **301**. In other words, the beacon transmission announcing the number of SS slots **304** precedes the SS slots **304**. In some embodiments, the BFT period **306** is an association beamforming training (A-BFT) period, although this is not a requirement.

FIG. **4** illustrates a configuration of a sector-sweep slot, in accordance with some embodiments. The SS slot **304** comprises a first duration **404** for the number of SS frames per SS slot **304** announced by the initiating station **101**, and a second duration **408** for a single SS feedback frame. In some embodiments, each SS slot **304** may include propagation delay time (aPropDelay) **401** to account for a propagation delay between the initiating station **101** (FIG. **1**) and a responding station **102** (FIG. **1**), and beamforming interface space (BFIS) **403** (or a short inter Frame Space (SIFS)) between the first duration **404** and the second duration **408**. The first duration **404** may be a time duration (aSSDuration) for a responding station **102** to transmit the predetermined number of SS frames to the initiating station. The second duration **408** may be a time duration (aSSFBDuration) **408** for the initiating station **101** to transmit at least the single SS feedback frame to one of the responding stations **102**. In these embodiments, the BFIS **403** may be a constant and may also be provided after second duration **408**.

FIG. **5** illustrates communications between an initiating station and responding stations for multiple-access beamforming, in accordance with some embodiments. For multiple-access beamforming, the initiating station **101** may transmit one or more beacon frames **502** as a sector sweep **501** within the BT **302** of the current beacon interval **301** (FIG. **3**). The sector sweep **501** may comprise a plurality of beacon frames **502** and may indicate that the initiating station **101** wishes to perform BFT. The initiating station **101** may announce in the beacon transmission the number of SS slots **304** of the BFT period **306** (FIG. **3**) and the number of SS frames of each SS slot **304**.

The initiating station **101** may receive one or more SS frames **504**, **506** from two or more of the responding stations within one of the SS slots **304** of the BFT period **306** (FIG. **3**). In response, the initiating station **101** may transmit one or more SS feedback frames **508** to the responding stations **102** and **103** within the SS slot **304**. The SS feedback frames **508** may be used to indicate the antenna configuration for communication with the initiating station **101** to the responding stations **102** and **103**. In accordance with some embodiments, the responding stations **102** and **103** transmit a limited number of SS frames **504** per SS slot **304** based on the number of SS frames announced by the initiating station **101**. The responding stations may transmit any additional SS frames **504** in a next SS slot of the BFT period **306**.

In these embodiments, the number of SS frames per SS slot **304** that is announced in the beacon transmission may be a total number of SS frames that can be transmitted in an SS slot **304**. If a responding station has, for example, thirty-six antenna sectors but the SS slot **304** can only admit six SS frames **504**, the responding station will use six SS slots **304** to complete a full reverse sector sweep.

Although the network coordinator for millimeter-wave communication network **100** is described herein as the initiating station (i.e., the station that is initiating beamforming), this is not a requirement as any station, not necessarily the network coordinator, may operate as an initiating station and initiate beamforming.

In some embodiments, the initiating station **101** may perform multiple-access beamforming for scheduling A-BFT with one or more responding stations in millimeter-wave communication network **100**. In these embodiments, more than one responding station is able to schedule and perform A-BFT within a single beacon interval.

In some embodiments, the antenna configuration indicated in the SS feedback frames **508** may indicate an antenna sector **221** (FIG. **2**A) for each of the responding stations to use in communicating with the initiating station **101**. In these embodiments, the initiating station **101** may use the SS frames **504** from the responding stations to identify the antenna sector **221** of a responding station from which the highest quality SS frame was received. The initiating station may indicate the antenna sector **221** to the responding stations in an SS feedback frame **508** for use in subsequent communications by the responding stations. The SS frames **504** from the responding stations may also indicate to the initiating station **101** that a responding station wishes to complete BFT and subsequently communicate with the initiating station **101**. The SS frames **504** from the responding stations may also indicate to the initiating station **101** the antenna sector **221** that the initiating station is to use for communication with each responding station.

In some embodiments, the sector sweep **501** comprises a beacon frame **502** transmitted in each of a plurality of antenna sectors of the initiating station **101** during the current beacon transmission. The responding stations, such as responding stations **102** and **103**, may transmit one SS frame **504** in each of their antenna sectors. The responding stations **102** and **103** remain in a receive mode to receive a beacon frame and an SS feedback frame **508** from the initiating station **101**. The initiating station **101** may remain in a receive mode to receive an SS frame **504** from the responding stations **102** and **103**. In some embodiments, the responding stations **102** and **103** remain in an omni-directional receive mode to receive the SS feedback frames **508**, although this is not a requirement. In some embodiments, a responding station may transmit more than one SS frame **504** in each of their antenna sectors, although this is not a requirement.

Random Backoff Embodiments:

In accordance with some random-backoff embodiments, a responding station may initiate a random backoff procedure at the start of the BFT period **306** to determine with which SS slot **304** of the BFT period **306** to begin transmissions of the SS frames **504**. The responding station may limit the number of SS frames **504** transmitted per SS slot **304** as indicated by the initiating station **101** in the beacon transmission. The responding station may resume transmission of the SS frames **504** at a start of a next SS slot within the current BFT period **306** when the responding station **102** has more SS frames **504** to transmit.

In accordance with these random-backoff embodiments, when the responding station **102** does not receive an SS feedback frame **508** from the initiating station **101** until completion of a reverse sector sweep **503**, the responding station **102** may retransmit the SS frames **504** within the same BFT period **306** of the current beacon interval **301**. The responding station **102** may also initiate a random backoff procedure to determine which SS slot following the completion of a prior reverse sector sweep **503** to retransmit the SS frames **504**. SS frames **504** may be considered reverse SS frames.

In these random-backoff embodiments, the initiating station **101** may schedule time in the beacon interval **301** for each of the responding stations to complete beamforming, including performing a beamforming refinement phase (BRP) within the current beacon interval **301** or the next beacon interval. The initiating station **101** may transmit a schedule in SS feedback frames **508** to indicate to each responding station when to perform beamforming refinement. In these embodiments, feedback frames **508** may be referred to as grant frames. In some embodiments, the BRP may occur anytime in the beacon interval **301** after a responding station has completed the SS phase in the BFT period **306**. During the BRP, beamforming coefficients may be generated to direct antenna beams for reception and transmission of signals with the other station.

In some embodiments, the initiating station **101** may send more than a single SS feedback frame **508** within the SS slot **304** when there is time remaining in the SS slot **304**. In an example embodiment in which the size of SS slot **304** is eight frames, if there are two responding stations that have one and two antenna sectors respectively, only two SS frames are needed to complete a reverse sector sweep **503**. After completion of their reverse sector sweeps **503**, additional time remains in the current SS slot **304** for the initiating station **101** to send SS feedback frames **508** to both of these responding stations. In these embodiments, the second duration **408** (FIG. **4**) is not limited to a single SS feedback frame **508**.

FIG. **6** illustrates communications between an initiating station and responding stations for multiple-access beamforming, in accordance with some alternate embodiments. As shown in FIG. **6**, the initiating station **101** may transmit beacon frames **502** during beacon time **302**. In these alternate embodiments, a responding station, such as responding station **102**, may transmit one SS frame **604** within a first SS slot **603** of the BFT period **306** following the beacon transmission. When an SS feedback frame **608** is not received by the responding station **102** until after completion of its entire reverse sector sweep, the responding station **102** may initiate a backoff procedure to determine a backoff period **606** comprising a random number of SS slots **304** to delay transmissions of additional SS frames **605** within the BFT period **306**. At the completion of the SS frame **605**, the responding station **102** may switch to a receive mode to receive an SS feedback frame **609**. In these embodiments, a reverse sector sweep may comprise all SS frames transmitted by a responding station. The responding station may transmit one SS frame in each antenna sector.

In these alternate embodiments, a responding station **102** may refrain from delaying transmissions of the additional SS frames **605** after the backoff period **606** when an SS feedback frame is received during the backoff period **606**. The responding station may also stop transmitting any of the additional SS frames **605** after an SS feedback frame **609** is received.

In these alternate embodiments, when the remaining time in the BFT period **306** after the backoff period **606** is less than the time for an SS frame **605** and an SS feedback frame **608**, the responding station may remain in receive mode until the end of the BFT period (e.g., in case it is able to receive an SS feedback frame **609**).

As illustrated in the example of FIG. **6**, each responding station **102**, **103** and **104** may have a different number of antenna sectors and, accordingly, the time that each station completes a reverse transmit sector sweep is different. For example, responding station **102** may have a single antenna sector and transmit a single SS frame **604** for its reverse sector sweep, while responding station **103** may have three antenna sectors and may transmit three SS frames **614** for its reverse sector sweep, and responding station **104** may have sixteen antenna sectors and may transmit sixteen SS frames **624** for its reverse sector sweep. In this example, since responding station **103** did not receive a sector sweep feedback frame during transmission of it reverse sector sweep (i.e., three SS frames **614**), it may initiate a backoff procedure to determine a backoff period **616** to delay transmissions of additional reverse SS frames **615** within the BFT period **306**.

FIG. **7** is a block diagram of a millimeter-wave communication station, in accordance with some embodiments. Millimeter-wave communication station **700** may include, among other things, an array antenna **722**, beamforming circuitry **702**, transmitter circuitry **706**, receiver circuitry **708** and processing circuitry **704**. Millimeter-wave communication station **700** may be suitable for use as any one or more of millimeter-wave communication stations **101**-**104** (FIG. **1**) and as discussed above. Array antenna **722** may include a plurality of antenna elements and may be configured to communicate in a plurality of antenna sectors, such as antenna sectors **221** FIG. **2**A. In some alternate embodiments, millimeter-wave communication station **700** may utilize a switched-beam antenna, although the scope of the embodiments is not limited in this respect. In some alternate embodiments, millimeter-wave communication station **700** may utilize a single antenna element, although the scope of the embodiments is not limited in this respect.

In accordance with some embodiments, beamforming circuitry **702** may configure array antenna **722** to transmit an SS frame (e.g., one of beacon frames **502** of FIG. **5**) separately in each of the antenna sectors **221**. Beamforming circuitry **702** may also configure array antenna **722** to receive the reverse sector-sweep frames (e.g., frames **504** and **506** of FIG. **5**).

In accordance with some embodiments, when millimeter-wave communication station **700** operates as an initiating station **101** for performing multiple-access beamforming with one or more responding stations, such as responding stations **102** and **103**, the processing circuitry **704** may be configured to announce a number of SS slots **304** (FIG. **3**) of a BFT period **306** (FIG. **3**) and a number of SS frames of each SS slot **304**. The receiver circuitry **708** may be configured to receive one or more SS frames **504**, **506** from two or more of the responding stations within one of the SS slots **304** of the BFT period **306**. The transmitter circuitry **706** may be configured to transmit one or more SS feedback frames **508** to the responding stations within the one SS slot **304** to indicate to the responding stations an antenna configuration for communication with the initiating station **101**.

In accordance with some embodiments, when millimeter-wave communication station **700** operates as a responding station, such as responding station **102**, for performing multiple-access beamforming with an initiating station, the processing circuitry **704** may receive an announcement from an initiating station, such as initiating station **101**, announcing a number of SS slots **304** of a BFT period **306** and a number of SS frames of each SS slot **304**. The transmitter circuitry **706** may transmit one or more SS frames **504**, **506** to the initiation station within one of the SS slots **304** of the BFT period **306**. The receiver circuitry **708** may be configured to receive one or more SS feedback frames **508** within the one SS slot **304** indicating an antenna configuration for communication with the initiating station. The responding station may be configured to transmit a limited number of SS frames **504** per SS slot **304** based on the number of SS frames announced by the initiating station, and each transmitted SS frame from the initiating station may indicate the an antenna configuration for communicating with the responding station. The responding station may also be configured to transmit any additional SS frames **504** in a next SS slot of the beamforming training period **306**.

In accordance with some embodiments, when the millimeter-wave communication station **700** operates as a responding station, such as responding station **102**, for performing multiple-access beamforming with an initiating station, such as initiating station **101**, the processing circuitry **704** may be configured to initiate a random backoff procedure at the start of a BFT period **306** to determine which SS slot **304** of the BFT period **306** to begin transmissions of an SS frame **504**. The processing circuitry **704** may also be configured to limit a number of SS frames **504** transmitted per SS slot **304** as indicated by the initiating station. The transmitter circuitry **706** may be configured to resume transmission of SS frames **504** at a start of a next SS slot within a current BFT period **306** when the responding station has more SS frames **504** to transmit.

Millimeter-wave communication station **700** may include other circuitry for communicating millimeter-wave wireless communication signals, including 60 GHz wireless technologies. In some embodiments, millimeter-wave communication station **700** can be used to provide a flexible interface that can be efficiently embedded into home media gateways, cell phones, flat panel televisions (TVs), set-top boxes, Blu-ray players, digital cameras, personal computers (PCs), laptops, and many other multimedia and communication devices. Although millimeter-wave communication station **700** is illustrated as having several separate functional elements, one or more of the functional elements may be combined and may be implemented by combinations of software-configured elements, such as processing elements including digital signal processors (DSPs), and/or other hardware elements. For example, some elements may comprise one or more microprocessors, DSPs, application specific integrated circuits (ASICs), radio-frequency integrated circuits (RFICs) and combinations of various hardware and logic circuitry for performing at least the functions described herein. In some embodiments, the functional elements of millimeter-wave communication station **700** may refer to one or more processes operating on one or more processing elements.

FIG. **8** is a procedure for multiple-access beamforming, in accordance with some embodiments. Procedure **800** may be performed by millimeter-wave communication stations, such as millimeter-wave communication stations **101**-**104** (FIG. **1**).

In operation **802**, the initiating station **101** may announce the number of SS slots **304** (FIG. **3**) of a BFT period **306** (FIG. **3**) and a number of SS frames of each SS slot **304**.

In operation **804**, the initiating station **101** may receive one or more SS frames **504**, **506** (FIG. **5**) from two or more of the responding stations within one of the SS slots **304** of the BFT period **306**. The responding stations may transmit a limited number of SS frames **504** per SS slot **304** based on the number of SS frames announced by the initiating station **101**.

In operation **806**, the initiating station may transmit one or more SS feedback frames **508** (FIG. **5**) to the responding stations within the one SS slot **304** to indicate an antenna configuration to the responding stations for communication with the initiating station **101**. The responding stations may transmit any additional SS frames **504** in a next SS slot of the beamforming training period **306**.

The Abstract is provided to comply with 37 C.F.R. Section 1.72(b) requiring an abstract that will allow the reader to ascertain the nature and gist of the technical disclosure. It is submitted with the understanding that it will not be used to limit or interpret the scope or meaning of the claims. The following claims are hereby incorporated into the detailed description, with each claim standing on its own as a separate embodiment.

What is claimed is:

1. An apparatus for a wireless communication device, the apparatus comprising:

receiver circuitry configured to receive RF signals including, during a beacon interval, an announcement of an indication of a number of sector-sweep slots that are to occur in a subsequent association beamforming training period (A-BFT) during the beacon interval within which the announcement is received, the sector-sweep slots comprising available time slots;

processing circuitry configured to use a random backoff procedure to determine a backoff amount to delay transmission of sector-sweep frames of a reverse sector sweep within a first of the sector-sweep slots; and

transmitter circuitry configured to transmit RE signals including at least some of the sector-sweep frames of the reverse sector sweep during the sector-sweep slot at a time based on the backoff amount, the processing circuitry to configure the receiver circuitry and the transmitter circuitry,

wherein a number of sector-sweep frames of the reverse sector sweep is based on a number of antenna sectors,

wherein when additional sector-sweep frames of the reverse sector sweep are to be transmitted, the processing circuitry is configured to decrease the backoff amount for transmission the additional sector-sweep frames in a next sector-sweep slot of the A-BFT.

2. The apparatus of claim 1, wherein the receiver circuitry is further configured by the processing circuitry to receive a feedback frame during the first sector-sweep slot in response to the transmission of the sector-sweep frames of the reverse sector-sweep,

wherein when the feedback frame is not received during the first sector-sweep slot, the processing circuitry is configured to decrease the backoff amount for of transmission the sector-sweep frames in the next sector-sweep slot of the A-BFT.

3. The apparatus of claim 2, wherein the processing circuitry further configures the transceiver circuitry and the receiver circuitry to perform a beamforming refinement phase subsequent to the A-BFT.

4. The apparatus of claim 2, wherein the processing circuitry further configures the transceiver circuitry and the receiver circuitry to perform the beamforming refinement phase during a same beacon interval as the reverse sector sweep.

5. A method of wireless communication performed by a wireless communication device, the method comprising:

receiving, by a responding station during a beacon interval, an announcement of an indication of a number of sector-sweep slots that are to occur in a subsequent association beamforming training period (A-BFT) during the beacon interval within which the announcement is received, the sector-sweep slots comprising available time slots;

using a random backoff procedure to determine a backoff amount to delay transmission of sector-sweep frames of a reverse sector sweep within a first of the sector-sweep slots; and

transmitting RF signals including at least some of the sector-sweep frames of the reverse sector sweep during the first sector-sweep slot at a time based on the backoff amount,

wherein a number of sector-sweep frames of the reverse sector sweep is based on a number of antenna sectors,

wherein when additional sector-sweep frames of the reverse sector sweep are to be transmitted, the method further comprises decreasing the backoff amount for transmission the additional sector-sweep frames in a next sector-sweep slot of the A-BFT.

6. The method of claim 5, further comprising receiving a feedback frame during the first sector-sweep slot in response to the transmission of the sector-sweep frames of the reverse sector-sweep,

wherein when the feedback frame is not received during the first sector-sweep slot, the processing circuitry is configured to decrease the backoff amount for of transmission the sector- sweep frames in the next sector-sweep slot of the A-BFT.

7. The method of claim 6, further comprising performing a beamforming refinement phase subsequent to the A-BFT.

8. The method of claim 6, further comprising performing a beamforming refinement phase during a same beacon interval as the reverse sector sweep.

9. An apparatus of a wireless communication device configured to operate as a responding station in a wireless communication network, the apparatus comprising: one or more processors and memory, programmed to provide instructions to cause transceiver circuitry of the wireless communication device to:

receive RF signals including during a beacon interval, an announcement of an indication of a number of sector-sweep slots that are to occur in a subsequent association beamforming training period (A-BFT) during a same beacon interval as the announcement, the sector-sweep slots comprising available time slots;

use a random backoff procedure to determine a backoff amount to delay transmission of sector-sweep frames of a reverse sector sweep within a first of the sector-sweep slots; and

transmit RF signals including at least some of the sector-sweep frames of the reverse sector sweep during the sector-sweep slot at a time based on the backoff amount,

wherein a number of sector-sweep frames of the reverse sector sweep is based on a number of antenna sectors,

wherein when additional sector-sweep frames of the reverse sector sweep are to be transmitted, the one or more processors are configured to decrease the backoff amount for transmission the additional sector-sweep frames in a next sector-sweep slot of the A-BFT.

10. The apparatus of claim 9, wherein the instructions further cause the transceiver circuitry to receive a feedback frame during the first sector-sweep slot in response to the transmission of the sector-sweep frames of the reverse sector-sweep,

wherein when the feedback frame is not received during the first sector-sweep slot, the processing circuitry is configured to decrease the backoff amount for of transmission the sector-sweep frames in the next sector-sweep slot of the A-BFT.

11. The apparatus of claim 10, wherein the instructions further cause the transceiver circuitry to perform a beamforming refinement phase subsequent to the A-BFT.

12. The apparatus of claim 10, wherein the instructions further cause the transceiver circuitry to perform a beamforming refinement phase during a same beacon interval as the reverse sector sweep.

13. An apparatus for a wireless communication device, the apparatus comprising:

transmitter circuitry configured to transmit RF signals including an announcement by an initiating station during a beacon interval, the announcement including an indication of a number of sector-sweep slots that are to occur during a subsequent association beamforming training period (A-BFT) during a same beacon interval as the announcement, the sector-sweep slots comprising available time slots; and

receiver circuitry, coupled to the transmitter circuitry, configured to receive RF signals including at least some sector-sweep frames of a reverse sector sweep from a responder station during a first sector-sweep slot after a time based on a backoff amount,

wherein a number of sector-sweep frames of the reverse sector sweep is based on a number of antenna sectors,

wherein the receiver circuitry is further configured to receive additional sector-sweep frames of the reverse sector sweep in a next sector-sweep slot of the A-BFT after a decreased backoff amount.

**14**. The apparatus of claim **13**, wherein the receiver circuitry is configured to receive a reverse sector-sweep frame from a responding station during one of the indicated slots, and

wherein the transmitter circuitry is configured to transmit a feedback frame to the responding station during said one of the indicated slots.

**15**. The apparatus of claim **14**, wherein the receiver circuitry and the transmitter circuitry are further configured to perform a beamforming refinement phase subsequent to said A-BFT.

**16**. The apparatus of claim **14**, wherein the receiver circuitry and the transmitter circuitry are further configured to perform a beamforming refinement phase during a same beacon interval.

**17**. A method of wireless communication performed by a wireless communication device, comprising:

transmitting RF signals including an announcement by an initiating station during a beacon interval, the announcement including an indication of a number of sector-sweep slots that are to occur during a subsequent association beamforming training period (A-BFT) during a same beacon interval as the announcement, the sector-sweep slots comprising available time slots; and

receiving RF signals including at least some sector-sweep frames of a reverse sector sweep from a responder station during a first sector-sweep slot after a time based on a backoff amount,

wherein a number of sector-sweep frames of the reverse sector sweep is based on a number of antenna sectors,

wherein the method further includes receiving additional sector-sweep frames of the reverse sector sweep in a next sector-sweep slot of the A-BFT after a decreased backoff amount.

**18**. The method of claim **17**, further comprising:

receiving a reverse sector-sweep frame from a responding station during one of the indicated slots; and

transmitting a feedback frame to the responding station during said one of the indicated slots.

**19**. The method of claim **18**, further comprising performing a beamforming refinement phase subsequent to said A-BFT.

**20**. The method of claim **18**, further comprising performing a. beamforming refinement phase during a same beacon interval.

**21**. An apparatus of a wireless communication device, the apparatus comprising one or more software-configured elements arranged to configure the wireless communication device for wireless communication, the one or more software-configured elements comprising:

one or more processors and memory, programmed to provide instructions to cause:

transceiver circuitry of an initiating station to transmit RF signals including an announcement during a beacon interval, the announcement including an indication of a number of sector-sweep slots that are to occur during a subsequent association beamforming training period (A-BFT) during a same beacon interval as the announcement, the sector-sweep slots comprising available time slots; and

receiver circuitry to receive RF signals including at least some sector-sweep frames of a reverse sector sweep from a responder station during a first sector-sweep slot after a time based on a backoff amount,

wherein a number of sector-sweep frames of the reverse sector sweep is based on a number of antenna sectors,

wherein the receiver circuitry is further configured to receive additional sector-sweep frames of the reverse sector sweep in a next sector-sweep slot of the A-BFT after a decreased backoff amount.

**22**. The apparatus of claim **21**, wherein the instructions further configure the transceiver circuitry to:

a reverse sector-sweep frame from a responding station during one of indicated slots; and

transmit a feedback frame to the responding station during said one of the indicated slots.

**23**. The apparatus of claim **22**, wherein the instructions further cause the transceiver circuitry to perform a beamforming refinement phase subsequent to said A-BFT.

**24**. The apparatus of claim **22**, wherein the instructions further cause the transceiver circuitry to perform a beamforming refinement phase during a same beacon interval.

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